Ultrafast Optical Response of a High-Reflectivity GaAs/AlAs Bragg Mirror

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The ultrafast response of a high-reflectivity GaAs/AlAs Bragg mirror to optical pumping is investigated for all-optical switching applications. Both Kerr and free carrier nonlinearities are induced with 100 fs, 780 nm pulses with a fluence of 0.64 kJ/m^2 and 0.8 kJ/m^2. The absolute transmission of the mirror at 931 nm increases by a factor of 27 from 0.0024% to 0.065% on a picosecond timescale. These results demonstrate the potential for a high-reflectivity ultrafast switchable mirror for quantum optics and optical communication applications. A design is proposed for a structure to be pumped below the bandgaps of the semiconductor mirror materials. Theoretical calculations on this structure show switching ratios up to 2200 corresponding to switching from 0.017% to 37.4% transmission.

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High-finesse optical cavities are of interest in quantum optics experiments, in particular for cavity quantum electrodynamics [1] and quantum state storage [2]. In many of these experiments it would be beneficial to be able to switch light in and out of a cavity on a fast timescale. Common cavity switching techniques use intracavity elements which unavoidably introduce additional cavity losses, limiting the finesse. In addition, switching elements such as acousto-optic modulators or Pockels cells are limited to timescales longer than tens of picoseconds.

Instead, we propose to switch the finesse of the cavity by switching one of the cavity end mirrors. The high-reflectivity cavity mirrors are composed of alternating layers of two different dielectric materials. Ideally the layer thicknesses in this Bragg mirror are $\lambda/4n$, where n is the refractive index of each of the materials and λ is the central wavelength of the reflected light. If the index of refraction of at least one of the materials can be switched rapidly, the reflectivity of the mirror will change on the same time scale. The change in n alters the ideal $\lambda/4n$ length ratio in the layers and the index contrast between the two materials. This process can be used for ultrafast all optical switching of a Bragg mirror [3, 4, 5, 6].

Similarly, switching in two and three dimensional photonic crystals [7, 8, 9] and switching using other mechanisms, such as spin-polarization relaxation [10] and saturable absorption [11], has been studied.

This earlier work has focused primarily on switching by large absolute percentages. However, to build a high-finesse switchable cavity a mirror with high initial reflectivity a large switching ratio is required. In this letter we present time resolved pump-probe measurements of the change in transmission of a GaAs/AlAs Bragg mirror under intense optical pumping.

A switchable mirror with high initial reflectivity requires materials that have low absorption at the desired operation wavelength, and a large index contrast is desirable in order to keep the mirrors as thin as possible. At least one material must posses a large nonlinear index of refraction to allow effective all-optical switching. GaAs and AlAs meet these criteria and mirrors with ∼30 layer pairs can be grown with reflectivities > 99.99%. GaAs and AlAs have a Kerr nonlinearity and in addition, the nonlinearity in index of refraction related to free carriers in GaAs has previously been studied [12].

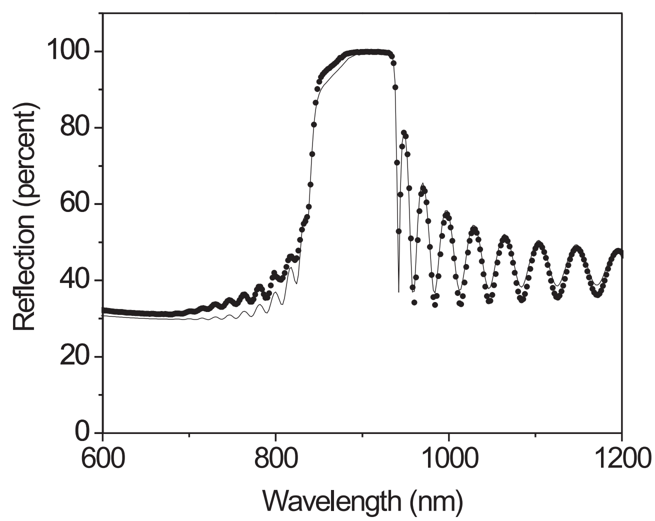

FIG. 1: Measured reflectivity (circles) and calculated reflectivity (solid line) of a 30 layer pair GaAs/AlAs Bragg mirror at 12.5° angle of incidence. The mirror is designed to have maximum reflectivity at 892nm for normal incidence.

The sample is a 30 pair GaAs/AlAs Bragg mirror on a GaAs substrate with a ∼50 nm spacer layer of $Al_{0.4}Ga_{0.6}As$. The thicknesses of the GaAs and AlAs layers are 61.8 nm and 75.0 nm respectively, corresponding to $\lambda/4n$ for a wavelength of 892 nm. The measured reflectivity (circles) and calculated reflectivity (solid line) as a function of wavelength at a 12.5° angle of incidence

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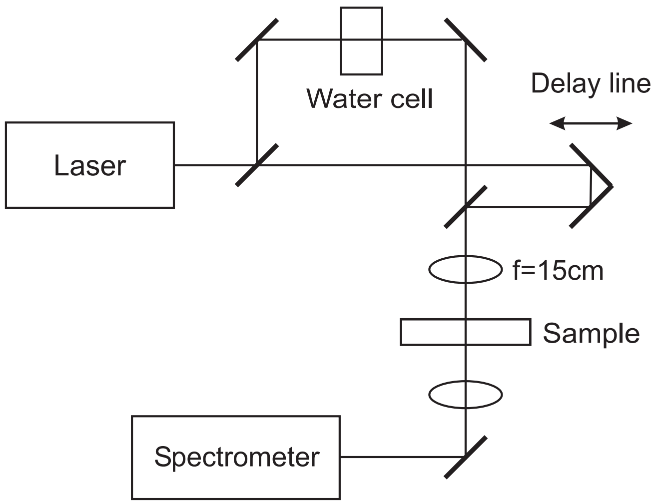

FIG. 2: Setup used to measure transmission through the mirror as a function of temporal pump-probe overlap. The probe is a broadband white light created by continuum generation with part of the pump light. The delay line in the pump path is scanned as transmission is measured in a spectrometer.

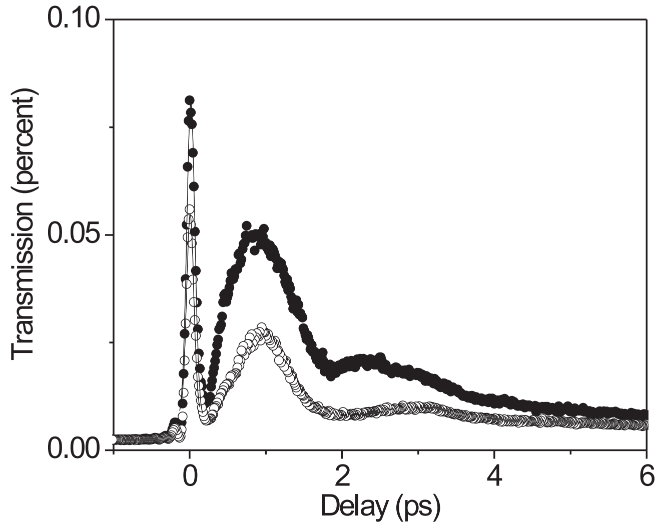

FIG. 3: Transmission at a wavelength of 931 nm as a function of probe delay for a pump fluence 0.8 kJ/m^2 (solid circles) and 0.64 kJ/m^2 (open circles).

is shown in figure 1. The asymmetry in the reflectivity is caused by absorption in the GaAs for photon energies larger than the bandgap of the GaAs.

The change in transmission through the sample as a function of the delay between pump and probe pulses is studied using the setup shown in figure 2. The light from a regeneratively amplified titanium sapphire femtosecond mode-locked laser at 780 nm with $\sim$100 fs pulse width and 40 kHz repetition rate is used as the pump. A portion of the light is split off and focused into a cell of flowing water, generating ultrafast white light probe pulses [13]. The pump and probe are combined on a dichroic mirror that reflects the 780nm pump beam and transmits the white light probe for $\lambda > 820$ nm such that they propagate collinearly. The pump and probe are then focused to a 30 μm radius spot on the sample with a f=15 cm lens. The collinearity of the pump and probe ensure good overlap on the sample. The pump beam path has a delay line which is scanned and at each position a spectrum of the transmitted light is measured using a spectrometer with a cooled charged-coupled device (CCD) camera. The pump light is absorbed in the sample, any residual pump light is at a different wavelength from the probe and does not interfere with the spectral measurement. A measurement of the transmission demonstrates the ability to switch the light out of a high-finesse cavity, as this requires a mirror that has an increase in transmission under optical pumping.

The transmission through the GaAs/AlAs mirror at 931nm for a pump fluence of 0.8 kJ/m^2 (solid circles) and 0.64 kJ/m^2 (open circles) as a function of pump probe delay is shown in figure 3. These fluences correspond to 80% and 64% of the damage threshold for GaAs [12]. At negative delay the transmission is constant. The initial fast response, peaking at maximal pump probe overlap, is attributed to the Kerr nonlinearity in GaAs and AlAs which changes the index of refraction of both materials, leading to an increase in transmission of the mirror. At 931nm this change is a 27 time increase in transmission; from a transmission of 0.0024% to 0.065%. The first peak is fit to a Gaussian with a full width at half maximum of $\sim$ 100 fs, consistent with the assumption that the switching is due to an instantaneous (Kerr) nonlinearity. The peak of the Gaussian corresponds to zero delay.

The second, lower but broader, peak is related to the presence of free carriers that induce a change in the index of refraction and increase the transmission of the mirror. Because the pump energy is below the bandgap of AlAs, the free carriers are created predominantly in the GaAs. A number of theoretical models for this change in index of refraction have been introduced. For the intense pump pulses used in our experiment, electrostatic screening and many body effects from the large number of free carriers are responsible for the index change [14, 15].

We also attribute the third, smaller peak after 2.5 ps, to the behavior of free carriers in the GaAs. A detailed analysis would require insight in the complicated dynamics of a high density of free carriers in GaAs that interact with the lattice and is beyond the scope of our experiments. Thermal effects in GaAs are typically observed on timescales $\sim$5 ps [12], and are responsible for the small offset observed in Fig. 3 at 6 ps.

Figure 4a shows the transmission as a function of wavelength for the unpumped mirror (solid triangles), the mirror at zero delay for a pump fluence of 0.8 kJ/m^2 (solid circles) and 0.64 kJ/m^2 (open circles). The ratio of the transmission in the pumped versus unpumped state is shown in figure 4b and is largest for the longer wavelengths and at a pump fluence of 0.8 kJ/m^2. The

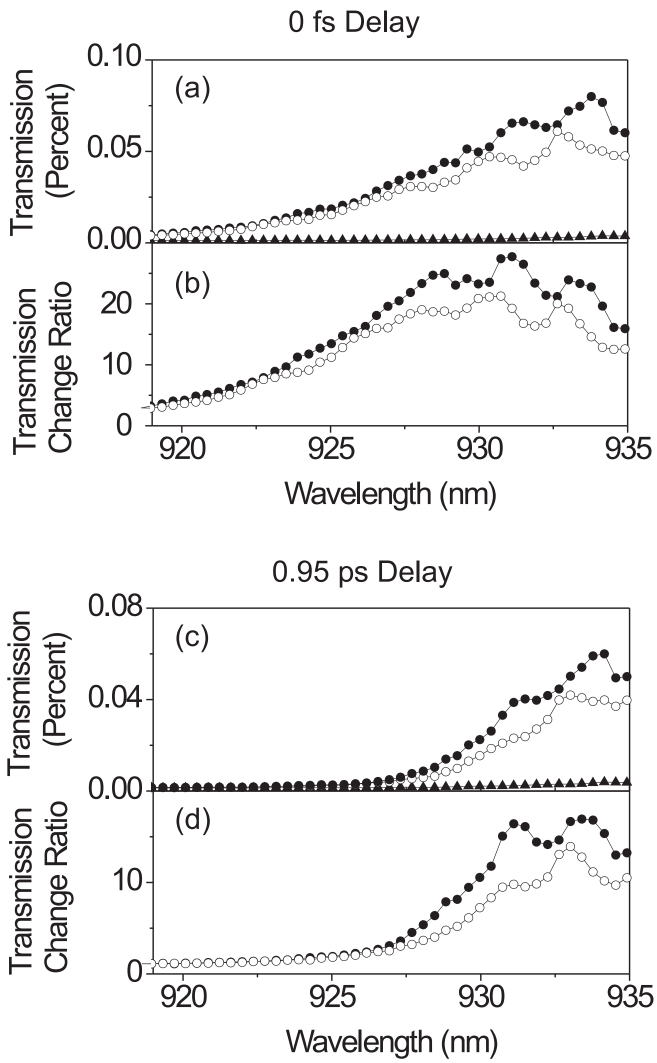

FIG. 4: Transmission spectrum for umpumped mirror (triangles) at maximal pump probe overlap (a) and at the second peak in transmission, a 0.95 fs delay (c) for pump fluence of 0.8 kJ/m^2 (solid circles) and 0.64 kJ/m^2 (open circles). The switching occurs over the whole wavelength range measured. The ratio of the pumped transmission to the umpumped transmission at zero delay (b) and 0.95 fs delay (d). At zero delay the largest change occurs for pump fluence of 0.8 kJ/m^2 at 931nm, a ratio of 27. At a 945 fs delay the largest change occurs for pump fluence of 0.8 kJ/m^2 at 933nm, a ratio of 17.

maximum change is a 27 time increase in transmission at a wavelength of 931 nm. The ratio of change is larger for the longer wavelengths, closer to the edge of the stop band of the Bragg mirror. There are two mechanisms that contribute to this effect. An overall change in the refractive index of the layers shifts the center wavelength of the Bragg mirror. In addition, a reduced index contrast between the layers narrows the width of the stop band of the Bragg mirror.

The transmission at 0.95 ps delay, corresponding to the second peak in transmission, is shown in figure 4c. The overall switching ratio (figure 4d) is less than that at zero delay with a maximum ratio of 17 and an absolute change from 0.0032% to 0.054%.

The absorption of the pump in the sample is assumed to be linear in the GaAs layers and negligible in the AlAs. With an absorption coefficient of 1.5$\times$ 10^4 cm^{-1} at 780 nm the 1/e point for absorption of the pump is after $\sim$11 layer pairs. The different pump intensity in the different layers produces a different change in index of refraction for each layer, only switching the top layers of the mirror effectively. However, with lower absorption, the pump would propagate further into the mirror and the switching ratio would be much larger.

The observation of switching due to the Kerr nonlinearity in GaAs and AlAs demonstrates the potential to achieve a large switching ratio using a pump laser at an energy below the bandgap in GaAs. At this energy there is no linear absorption in the layers.

A 2x2 transfer matrix model for the transmission of a 30 layer pair GaAs/AlAs Bragg mirror with the substrate etched away is used to calculate the switching ratio for a 0.8 kJ/m^2 pump at 1060 nm. A two-photon absorption coefficient, $\beta = 23\ cm/GW$, [16] is used to calculate an absorption coefficient of the pump of $1.8 \times 10^6\ m^{-1}$ for the incident intensity. For the two-photon process, the point where the intensity drops to 1/e times the initial value is after after 22 layers, significantly larger than the 11 layers for pumping above the band gap. A nonlinear coefficient $n_2 =$ -6.6 $\times$ 10^{-13} cm^2/W [16] in the GaAs layers is assumed, where we have taken into account the colinear double beam configuration of the pump and probe [17]. Using the values above, a switching ratio of 2200 is calculated with transmission changing from 0.017% to 37.4% at 915nm. No data is available for the Kerr nonlinearity in AlAs, but the nonlinearity in AlAs below the bandgap is expected to be at least an order of magnitude smaller than that of GaAs according to the dependence of n_2 on the bandgap at pump energies below the bandgap [18, 19].

Using the Kerr nonlinearity to switch the mirror gives accurate control over switching times. Pump pulses in the range from tens of femtoseconds to tens of picoseconds could be used to achieve desired switching times.

In conclusion we have shown that the nonlinear index of refraction in GaAs and AlAs can be used to create a high-reflectivity GaAs/AlAs all optically switchable mirror. Switching is demonstrated with a maximum change of 27 times in transmission from 0.0024% to 0.065% at 931 nm. With a larger switching ratio such a mirror would make an excellent optical switch as one end mirror of a high-Q cavity. A switching ratio of 2200 is predicted for optical pumping at energies below the bandgap of the GaAs.

Acknowledgments

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